

New or ν Missing Energy? Discriminating Dark Matter from Neutrino Interactions at the LHC

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Missing energy signals such as monojets are a possible signature of Dark Matter (DM) at colliders. However, neutrino interactions beyond the Standard Model may also produce missing energy signals. In order to conclude that new “missing particles” are observed the hypothesis of BSM neutrino interactions must be rejected. In this paper, we first derive new limits on these Non-Standard neutrino Interactions (NSIs) from LHC monojet data. For heavy NSI mediators, these limits are much stronger than those coming from traditional low-energy ν scattering or ν oscillation experiments for some flavor structures. Monojet data alone can be used to infer the mass of the “missing particle” from the shape of the missing energy distribution. In particular, 13 TeV LHC data will have sensitivity to DM masses greater than ~ 1 TeV. In addition to the monojet channel, NSI can be probed in multi-lepton searches which we find to yield stronger limits at heavy mediator masses. The sensitivity offered by these multi-lepton channels provide a method to reject or confirm the DM hypothesis in missing energy searches.

I. INTRODUCTION

Missing energy signals are the tell-tale clue of the production of stable neutral objects. Indeed the imbalance of momentum and energy is in fact precisely the way in which the neutrino was first discovered. Supposing that the LHC finds anomalous “missing energy” events above SM backgrounds, the determination of its origin will be of paramount importance. As known sources of missing energy, a plausible origin of new missing energy data will be neutrinos. However, new neutral particles beyond Standard Model (BSM) such as dark matter can also produce missing energy signals at colliders.

In this paper we explore how LHC data can be used to distinguish these two potential sources of missing energy. We illustrate that both the DM mass and the $SU(2)$ charge of neutrinos can be used to discriminate between singlet DM and SM neutrinos.¹ For simplicity we will focus on the so-called “monojet” signature in which a single hard jet recoils against “nothing” [2–30]. Previous work in this direction using Tevatron and early LHC data was carried out in [11].

We begin by reviewing current experimental limits on neutrino-proton interactions in the context of effective field theory (EFT). Up to dimension 6, we can have

- Neutrino magnetic dipole moments:

$$\mathcal{L} \supset \mu_\nu F^{\mu\nu} \bar{\nu} \sigma_{\mu\nu} \nu, \quad (1)$$

where the spin matrix is $\sigma_{\mu\nu} \equiv i[\gamma_\mu, \gamma_\nu]/2$, μ_ν is the magnetic moment (measured in units of the Bohr magneton $\mu_B \equiv e/(2m_e)$, where e, m_e are the charge and mass of the electron).

- Non-standard neutrino interactions (NSIs),

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma_\rho \nu_\beta) (\bar{f} \gamma^\rho P f). \quad (2)$$

where the matrix $\varepsilon_{\alpha\beta}^{fP}$ specifies the strength of the ν - f interaction, in units of Fermi’s constant, $G_F \equiv 1/\sqrt{2}v_{EW}^2 \simeq 1.2 \times 10^{-5} \text{ GeV}^{-2}$, with $v_{EW} = 246 \text{ GeV}$. The labels α, β are flavor indices running over e, μ, τ , and P is a projection operator. We take f to be any SM fermion (though only the *vector* components of $f = e, u, d$ are relevant for neutrino oscillations).

Let us first consider whether neutrino magnetic moments below currents limits can produce sizeable missing energy at the LHC? For Majorana neutrinos the 3×3 matrix μ_ν does not have diagonal entries and is anti-symmetric, but is completely general if they are instead Dirac. In the SM the magnetic moment is proportional to the neutrino mass, and therefore extremely small, $\mu_\nu^{\text{SM}} \sim 10^{-20} \mu_B$. For Dirac neutrinos in BSM scenarios, naturalness considerations on the coefficients of effective operators imply, $\mu_\nu \lesssim 10^{-14} \mu_B$ [31], far below present experimental sensitivity. Finally for Majorana neutrinos reactor data as measured by the GEMMA spectrometer constrains, $\mu_\nu < 3.2 \times 10^{-11} \mu_B$, [32] while the 7 TeV LHC sensitivity is around $\sim 3 \times 10^{-5} \mu_B$ [33], far above what is allowed by reactor and solar data [34]. We conclude that neutrino magnetic moments will not produce sizeable missing energy at the LHC.

Proceeding now to operators of mass dimension 6, we turn our attention to the NSI operators between quarks-neutrinos. Non-standard neutrino interactions (NSIs)

¹ If DM itself transforms non-trivially under $SU(2)$ the situation is more complex. We leave for future work a systematic study in this direction but note that some of the implications of $SU(2)$ charged DM in a variety of representations has been studied in e.g. [1].

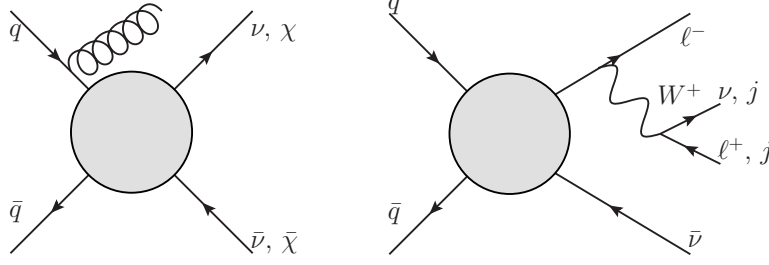


FIG. 1: Typical Feynman diagrams for $pp \rightarrow \bar{\nu}\nu(\bar{X}X) + j$ (left panel) and $pp \rightarrow \bar{\nu}\nu \rightarrow \ell^\mp + W^\pm + \bar{\nu}$ (right panel). Though singlet DM and neutrinos are largely degenerate in the former process, only SM neutrinos give rise to the latter process.

were first introduced in 1977 [35] and continue to be of wide phenomenological interest [11, 36–48] (see [36, 49] for reviews).

They are constrained by solar [37, 50–56], atmospheric [38, 39, 46, 57–60], long-baseline [41–43, 45, 48, 60, 61], collider [11, 44, 47, 62], cosmological [63], and neutrino scattering data [36, 40, 49].

The Lorentz structure of Eq. 2 can be understood as follows. First, assume that NSI can be parameterized as $\mathcal{O}_{NSI} = \mathcal{O}_\nu \otimes \mathcal{O}_f$ where $\mathcal{O}_\nu, \mathcal{O}_f$ are neutrino and SM fermion bilinears. Under the assumption that lepton number remains a good symmetry and only left-handed neutrinos enter into \mathcal{O}_{NSI} , all such operators can be decomposed into $(V - A) \otimes (V - A)$, $(V - A) \otimes (V + A)$ components.

One may worry that sizeable NSI would also induce large charged lepton interactions [36, 64, 65]. Indeed, to evade the very strong limits from the charged lepton equivalent of Eq. (2) we consider dimension-8 operators of the form [62]

$$\mathcal{L}_{NSI}^{\text{dim-8}} = -\frac{4\varepsilon_{\alpha\beta}^{fP}}{v_{EW}^4} (\overline{HL}_\alpha \gamma_\mu H L_\beta) (\bar{q}\gamma_\mu q) \quad (3)$$

where H is the SM Higgs doublet. In unitary gauge and upon electroweak (EW) symmetry breaking we can make the replacement $H \rightarrow (h + v_{EW})/\sqrt{2}$. Thus at low energies, one indeed generates Eq. (2) without charged lepton interactions of the same strength.

The remainder of this paper is organized as follows. First we introduce our simplified model and calculational framework in Sec. II. In Section III we derive new constraints on NSI based on the latest monojet data from the LHC. Then we turn to projections of monojet sensitivity at 13 TeV and the ability to infer the mass of the “missing particles” from the shape of the \cancel{E}_T distribution. We find that for contact interactions, DM masses $\gtrsim 700$ GeV can be discriminated from NSI with about 100 fb^{-1} of integrated luminosity. In Sect. IV we then use two distinct multi-lepton channels to probe NSI. These searches have neutrino flavor dependent sensitivity and have better sensitivity than monojets for heavy mediators of NSI. In Sec. V we discuss the complementarity of

these channels along with low-energy probes of NSI for DM-neutrino discrimination and conclude in Sec. VI.

II. MODEL AND CALCULATIONAL FRAMEWORK

In order to derive LHC limits on NSI/DM couplings ε we have implemented two models in the Universal Feyn-Rules Format (UFO) [66] by adding to the SM a spin-1 mediator, R^μ , which interacts with neutrinos, quarks and DM X through the phenomenological Lagrangians:

$$\begin{aligned} \mathcal{L}_{NSI} &= g_\nu (\bar{\nu} P_L \gamma_\mu \nu) R^\mu + (\bar{q} \gamma_\mu (g_q^V + g_q^A \gamma^5) q) R^\mu, \\ \mathcal{L}_{DM} &= g_X (\bar{X} \gamma_\mu X) R^\mu + (\bar{q} \gamma_\mu (g_q^V + g_q^A \gamma^5) q) R^\mu, \\ &\quad + m_X \bar{X} X \end{aligned} \quad (4)$$

where ν and q are summed over all neutrino and quark flavors respectively, and m_X is the DM mass. The Lagrangian \mathcal{L}_{NSI} correctly reproduces the contact interaction, Eq. (2) when the vector mass, m_R is large compared to the center of mass energy. Note that the DM literature tends to report limits on the scale of the dimension-six operator, Λ , defined as $(\bar{X} \gamma_\mu X)(q \gamma^\mu q)/\Lambda^2$. The conversion from Λ to the NSI ε parameter in this context is, $\varepsilon = (2G_F \Lambda^2)^{-1}$.

The main aim of this paper is to illustrate how \mathcal{L}_{NSI} can be discriminated from \mathcal{L}_{DM} and gauge the relevant parametric dependencies present in s -channel completions of NSI (t -channel completions are very strongly constrained [11, 47] and not considered further). For details on a more complete Z' model we refer the reader to the Appendix and to [67, 68] for additional models. Furthermore, it is important to highlight that a complete model typically produces signatures *in addition* to the monojet and multilepton channels we consider here, making our approach conservative.

Simplified models of the type in Eq. 4 have been studied extensively in the DM literature [7, 9, 10, 12, 13, 17, 29, 69–79]. While dijet searches provide additional constraints on the models considered here (see e.g. [13, 29]) both \mathcal{L}_{NSI} and \mathcal{L}_{DM} contribute equally to this channel and thus it is not a useful discriminatory tool.

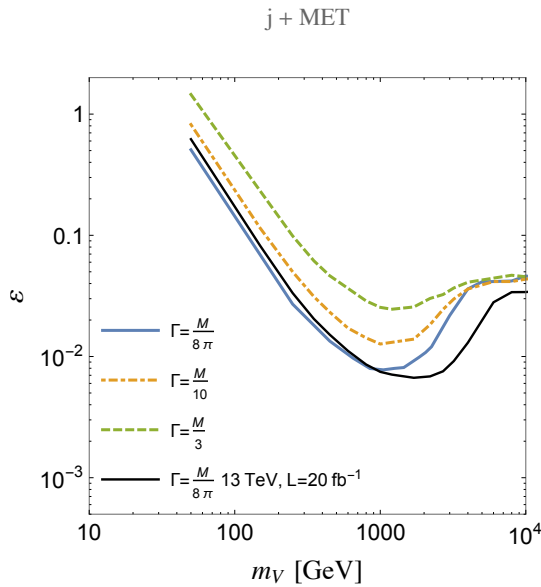


FIG. 2: Here we display the CMS monojet limits [88] on NSI at 95%CL for three different choices of the mediator width at $\sqrt{s} = 8$ TeV and with integrated luminosity $\mathcal{L} = 19.5 \text{ fb}^{-1}$. The black solid line denotes the expected limit at 95%CL with $\sqrt{s} = 13$ TeV and $L = 20 \text{ fb}^{-1}$.

Our calculational framework is as follows: To keep the analysis simple, we consider only vector couplings, i.e. $g_q^A = g_X^A = 0$. We import the UFO model into the MadGraph5_aMC@NLO framework [80], where helicity amplitudes are generated by the ALoha [81] code. The hard scattering simulation is then processed through parton showering and hadronization using Pythia 6 [82] and Pythia 8 [83]. Finally we performed a fast detector simulation for the monojet analysis, using both the PGS [84] and DELPHES [85] programs to check our results.

For the monojet computation we use the CTEQ 6L1 [86] set of parton distribution functions, as this is used by the experimental collaboration, and NNPDF 2.3 [87] for the other processes. We chose the default dynamical factorization and renormalization scales of MadGraph_aMC@NLO.

III. MONOJET SEARCHES

Any long-lived or stable neutral states, such as neutrinos and DM, with couplings to protons can lead to monojet events at the LHC. These monojet processes, depicted in Fig. 1 (*left*), are characterized by large missing transverse energy and a very hard jet. In [88], the CMS experiment searched for monojets with $\sqrt{s} = 8$ TeV in the center of mass energy and $\mathcal{L} = 19.5 \text{ fb}^{-1}$ of integrated luminosity, reporting an upper limit at 90%CL of $\varepsilon = 0.053$ for a vector operator and an invisible particle mass $m_X = 1$ GeV.

To estimate the NSI signal we compute the cross sec-

tions for the hard scattering process

$$pp \rightarrow V \rightarrow \bar{\nu}\nu + 1, 2 j, \quad (5)$$

with one and two jets (quarks or gluons), j using the framework described in sec. (II). In particular we use the MLM prescription [89] for matching matrix elements with soft jets from the parton shower. Following the CMS analysis [88] we require the leading jet to have $p_T(j) > 110$ GeV and to be in the central region of the detector $|\eta(j)| < 2.6$. Events with more than 3 jets with $p_T > 30$ GeV and $|\eta| < 4.5$ are discarded, while a second jet is allowed as long as the difference in azimuthal angle to the leading jet is less than 2.5, $\Delta\phi(j_1, j_2) < 2.5$. We further require the missing transverse energy $\cancel{E}_T > 450$ GeV, found to give the best discriminant.

With this analysis set-up we found excellent agreement in the shape of the missing transverse energy distribution for $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ SM background. We also found agreement within scale and PDF uncertainties for the number of events. We nevertheless use the fact that the collaboration provides a more precise prediction from data driven techniques and we rescale our predictions by a correction factor of 1.19 to agree with their prediction.

The CMS collaboration report 157 events as the upper 95% confidence level (CL) limit on the number of events from new physics. Note that a downward fluctuation in the observed number of events gives a constraint about 30% stronger than expected. We compute the resulting NSI limits that are shown in Fig. 2, as a function of the mediator mass and width ($\Gamma_V = \frac{m_V}{3}, \frac{m_V}{10}, \frac{m_V}{8\pi}$).

Note that *flavor diagonal* NSIs interfere with the dominant SM background process, $pp \rightarrow Z + j \rightarrow \bar{\nu}\nu + \text{jets}$. The strength of the effect depends on the Lorentz structure of the coupling, and the mass of the mediator. The effect is small in the contact interaction limit, $\lesssim 5\%$, but can be as large as 20% when the mass of the mediator is close to the Z mass. Although interference is a feature specific to the NSI case it only affects the total number of events and does not aid in distinguishing between dark matter and NSI. We shall therefore omit it in the following

A. Projection to $\sqrt{s} = 13$ TeV LHC and jet p_T shape analysis

The next LHC run at $\sqrt{s} = 13$ TeV will either further limit or discover NSI and/or DM in monojet searches. In Fig. 2 we show our projected LHC monojet 95%CL limit as the solid black line for $m_X = 0$ GeV at $\sqrt{s} = 13$ TeV with the luminosity $\mathcal{L} = 20 \text{ fb}^{-1}$ as expected for the first year of collisions. We use the same set-up used at $\sqrt{s} = 8$ TeV and the same normalization rescaling. We assume a systematic error of 5% and performed a χ^2 analysis with which the expected bounds at 8 TeV quoted by CMS were reproduced within error. At this luminosity the systematic error dominates and increasing

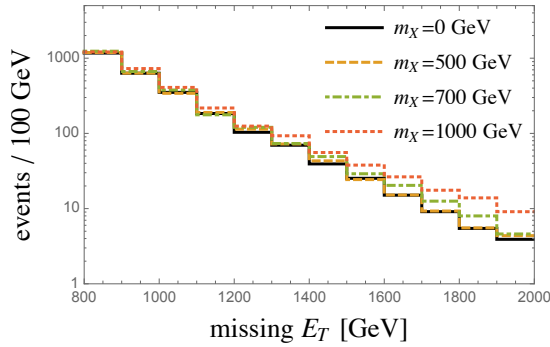


FIG. 3: Distribution of events in missing transverse energy, \cancel{E}_T , for $\sqrt{s} = 13$ TeV and $\mathcal{L} = 100 \text{ fb}^{-1}$ for DM masses $m_X = 0$ GeV, 500 GeV, 700 GeV and 1 TeV. Here each distribution is generated assuming contact interactions which produce an identical total number of events, with an interaction strength just below present bounds (see e.g. Fig. 2).

the luminosity further does not appreciably change the experimental sensitivity.

The first observable we use to distinguish NSI from DM is the monojet \cancel{E}_T distribution. Sufficiently heavy DM masses are kinematically relevant at LHC energies and affect the shape of the \cancel{E}_T distribution.

The allowed value of ε just below the 95%CL present limit is ~ 0.04 in the contact interaction limit, for massless missing energy particles. This situation, *i.e.* $\varepsilon = 0.04$, would produce a 2.9σ excess according to our projections for the first year Run II of the LHC. The same excess of events can be produced for lower ε but

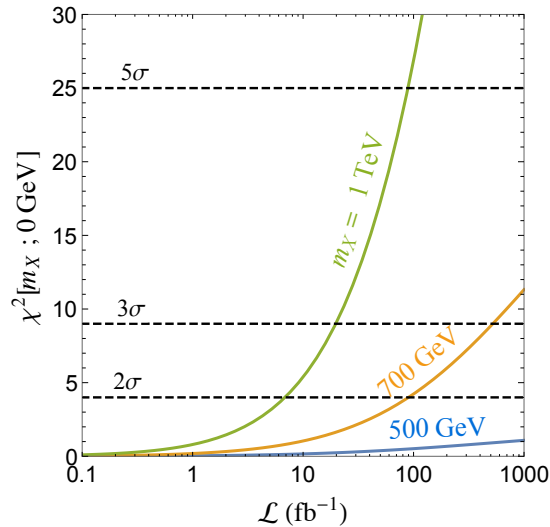


FIG. 4: χ^2 projection analysis. Here we generate events at $\sqrt{s} = 13$ TeV in a model with contact interactions just below present bounds with a 0 GeV DM mass. The $\chi^2[m_X; 0 \text{ GeV}]$ is computed by fitting $m_X = 500, 700, 1000$ GeV DM masses to the input data from a massless invisible particle. The 3σ , 4σ and 5σ confidence levels are plotted for reference.

lighter mediator mass or larger ε and heavier particles in the final state. In Fig. 3 we show the \cancel{E}_T distribution for $\mathcal{L} = 100 \text{ fb}^{-1}$ for DM masses, $m_X = 500, 700, 1000$ GeV. The total cross sections are all normalized to the $\varepsilon = 0.04$ massless case (shown in the projection Fig. 5) so that all signals produce the same total number of events with $\cancel{E}_T > 450$ GeV.

The shape of the \cancel{E}_T distributions clearly allow to distinguish between the heaviest and lightest DM mass. We quantify this in a simple χ^2 analysis. In addition to the statistical error, we assume a systematic error per bin of 5% for the background and 20% for the dark matter contribution, as reported in [88]. The χ^2 distribution is then given by

$$\chi^2[m_X; 0 \text{ GeV}] = \sum_i \left[\frac{S_i(m_X) - S_i(0 \text{ GeV})}{\sigma_i} \right]^2, \quad (6)$$

where $S_i(m_X)$ is the number of events in the i^{th} bin. The distribution is shown in Fig. 4 for the three masses $m_X = 500, 700, 1000$.

IV. MULTILEPTON SEARCHES

In addition to the monojet signal, NSI can produce signals in other channels due to the $SU(2)$ charge of neutrinos. For example, as shown in Fig. 1 one of the produced neutrinos can radiate a W boson that decays to either jets or $\ell + \nu$,

$$pp \rightarrow \bar{\nu}\nu \rightarrow \bar{\nu} + W^\pm \ell^\mp. \quad (7)$$

Multilepton searches of this type have been used previously to constrain NSI using LHC data [11, 44].

In order to exclude the NSI hypothesis and claim the discovery of a new source of missing energy, we must exclude all possible neutrino flavor structures of NSI. For this it is necessary to consider the lepton in the final state to be a tau, a muon or an electron. Since the mixed flavor interaction, *e.g.* $\varepsilon_{\tau\mu}$, $\varepsilon_{e\mu}$, will regardless produce one of these leptons, this condition is also sufficient to constrain mixed terms. For the muon and electron in the final state we have relied on the $\sqrt{s} = 8$ TeV and $\mathcal{L} = 20.3 \text{ fb}^{-1}$ ATLAS search for resonant diboson production where one boson decays leptonically and the other hadronically [91]. For the tau lepton final state we have used the ATLAS search for supersymmetry with large missing transverse energy, jets and at least one tau lepton, at $\sqrt{s} = 8$ TeV and $\mathcal{L} = 20.3 \text{ fb}^{-1}$ of data [90]. We will briefly describe each analysis and results in the following.

The searches we used are not optimized for the NSI signal topologies and we expect that dedicated analyses can improve our results. Moreover NSI can lead to signals not considered here but they are expected to be sub-dominant. For example $pp \rightarrow \nu\nu(Z \rightarrow jj/\ell^+\ell^-)$, where the neutrino radiates a Z boson will suffer from large background from Drell-Yan production. Similarly,

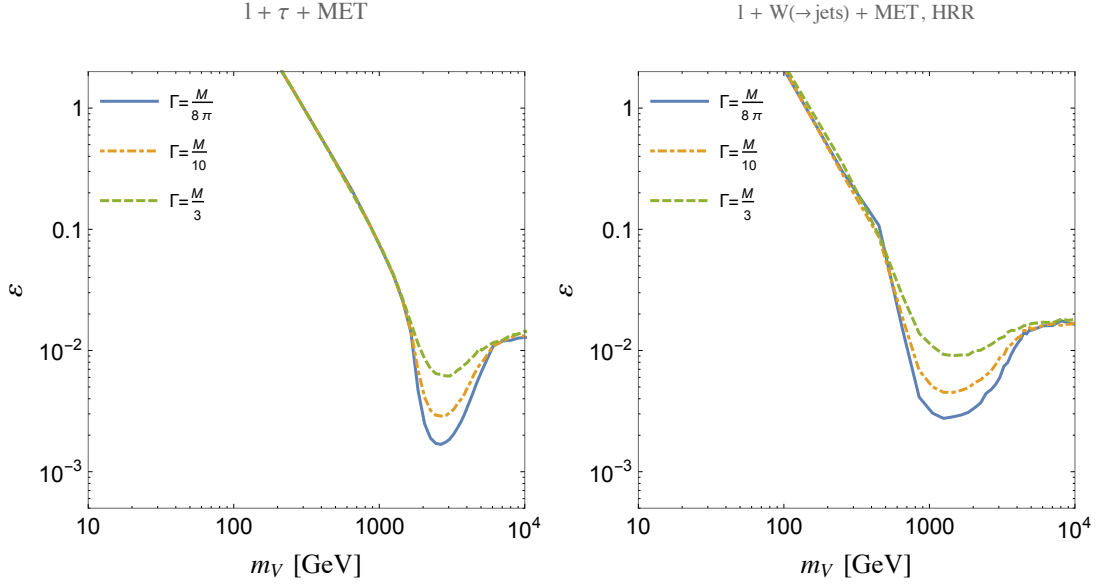


FIG. 5: Each panel displaying individual LHC search limits on NSI for three different choices of the mediator width. The *left* panel displays the $\tau + \ell + \text{MET}$ search from ATLAS [90], while the *right* panel shows the sensitivity from the $jj + \ell + \text{MET}$ search from ATLAS [91] (see text for details).

in $pp \rightarrow \nu \ell (W \rightarrow \ell \nu)$ with highly energetic $\ell^+ \ell^-$ system, the W cannot be reconstructed, suffering from many more backgrounds. Nonetheless, all these channels may contribute to put bounds on NSI and require a dedicated analysis.

We begin by considering hadronic decays of the W s, *i.e.*

$$\text{A. } pp \rightarrow \bar{\nu} + W^\pm \ell^\mp, W^\pm \rightarrow jj, \ell = e, \mu$$

In this analysis the W -boson is required to be highly boosted to reduce hadronic backgrounds. Consequently the two jets from the W are likely to appear as a single jet making jet substructure techniques relevant. The parton-level computation was passed through parton-showering and hadronization using *Pythia 8*.

We employ the event selection of the experimental analysis in [91]: Leptons are required to have transverse momentum $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$. Moreover, they are required to satisfy the following isolation criteria: the scalar sum of p_T of tracks with $p_T > 1 \text{ GeV}$ within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.2$ of the lepton track is required to be less than 15% of the lepton p_T . The missing transverse energy, defined as the negative of the vectorial sum of the transverse momenta of all electrons, muons and jets within $|\eta| < 4.9$, is required to be $\cancel{E}_T > 30 \text{ GeV}$.

We cluster the jets with two different jet definitions provided by *Fastjet 3.1.2* [92]. For the signal region where the W has large p_T and the jets cluster into a single 'fat' jet, we use the Cambridge algorithm. Otherwise, we use the anti- k_T algorithm with $R = 0.4$. The ATLAS analysis [91] defines three signal regions as: The

merged region (MR), the high- p_T resolved region (HRR) and the low- p_T resolved region (LRR) respectively. In the MR the largest p_T jet (J) is taken to represent a decayed W -boson, if it fulfills $p_T(J) > 400 \text{ GeV}$, $|\eta(J)| < 2$ and $65 \text{ GeV} < m(J) < 105 \text{ GeV}$ with the azimuthal angle difference between J and \cancel{E}_T satisfying $\Delta\phi(J, \cancel{E}_T) < 1$. Additionally, the p_T of the lepton and \cancel{E}_T system is required to be $p_T(\ell \cancel{E}_T) > 400 \text{ GeV}$.

If the event does not pass these cuts, we proceed to the resolved region, where the two leading 0.4 anti- k_T jets, $j_{1,2}$ reconstruct a decayed W boson if: $|\eta(j)| < 2.8$, $65 \text{ GeV} < m(jj) < 105 \text{ GeV}$ and $\Delta\phi(j_1, \cancel{E}_T) < 1$. The HRR (LRR) is defined by $p_T(jj) > 300(100) \text{ GeV}$, $p_T(j) > 80(30) \text{ GeV}$ and $p_T(\ell \cancel{E}_T) > 300(100) \text{ GeV}$.

After normalizing with an approximate NLO K-factor of $K=1.7$ [93], we get reasonable agreement in all three regions for the number of events expected from the SM diboson background. Therefore we assume that this simple analysis is accurate enough for our needs.

We used the model described by Eq. (4) to estimate the visible cross sections, σ_S , and associated number of events, $S = \sigma_S \mathcal{L}$ of the NSI signal, where the luminosity is $\mathcal{L} = 20.3 \text{ fb}^{-1}$. We rescale our prediction by a K-factor $K = 1.2$ to account for QCD corrections extracted from on-shell Z' production [94]. We moreover assumed a conservative flat theoretical error of 30% to account for PDF and scale uncertainty. The SM prediction for the total number of events and uncertainty, $B \pm \sigma_B$, is 161500 ± 2300 , 870 ± 40 and 295 ± 22 for LRR, HRR and MR respectively and the observed number of events, $N^{obs} = 157837$, 801 and 295 respectively. We summed the errors in quadrature, $\sigma_{TOT}^2 = \sigma_B^2 + S + (0.3S)^2$ and estimate the 95% CL upper limit on S using a χ^2 analysis,

solving for S the equation

$$\left(\frac{S+B-N^{obs}}{\sigma_{TOT}}\right)^2 = \chi^2_{0.05}(\text{d.o.f.} = 1) = 3.84. \quad (8)$$

The resulting limits in terms of ε are shown in Fig. 6.

Next we will consider leptonically decaying W bosons

$$\text{B. } pp \rightarrow \bar{\nu} + W^\pm \tau^\mp, W^\pm \rightarrow \ell \nu \text{ and } pp \rightarrow \bar{\nu} + W^\pm \ell^\mp, \\ W^\pm \rightarrow \tau \nu, \tau \rightarrow \text{hadrons}, \ell = e, \mu$$

The signal region defined in the ATLAS search [90] relevant for our final state is referred as the τ +lepton “GMSB signal” region, which requires a reconstructed hadronically decayed tau lepton and a single isolated electron or muon. Non standard neutrino interactions involving a tau lepton will contribute to this process, but other NSI flavour structures without a tau leptons will equally contribute when the W boson decays to a tau lepton and tau neutrino.

In our analysis we assume the tau is reconstructed with 70% of efficiency in this region, as reported in the analysis. In addition, we reproduce the kinematical cuts given therein: $p_T(\ell) > 25$ GeV, $p_T(\tau) > 20$ GeV, lepton transverse mass, $m_T(\ell) > 100$ GeV, defined by

$$m_T(\ell) = \sqrt{2p_T(\ell)\cancel{E}_T(1 - \cos(\Delta\phi(\ell, \cancel{E}_T)))} \quad (9)$$

and $m_{\text{eff}} > 1700$ GeV, where

$$m_{\text{eff}} = p_T(\ell) + p_T(\tau) + \cancel{E}_T. \quad (10)$$

The 95% CL limit on the visible cross section provided by the ATLAS collaboration is 0.20 fb for $\tau + e$ channel and 0.26 fb for the $\tau + \mu$ channel. Using these numbers we find the 95%CL exclusion limit shown in Fig. 6 as the blue dot-dashed line. The limit shown is for NSI involving a tau lepton, $\varepsilon_{\tau\tau}$, however the difference with respect to other flavour structures is small. For ε_{ee} it is only a few percent, and for $\varepsilon_{\mu\mu}$ it is about 15% due to the weaker experimental upper limit on the muon channel.

V. DISCUSSION

After deriving new limits on NSI, we finally asses what future LHC data can unveil. If anomalous missing energy events appear in the next run of the LHC, they will be consistent with either DM or NSI just at the border of the current constraints. If the events are due to TeV scale DM, then \cancel{E}_T shape analysis will be enough to rule out NSIs as the origin. If that is not the case, then we can still use multi-lepton channels to help discriminate between NSIs and DM. To illustrate this point we consider three distinct benchmark scenarios:

- **Benchmark A**, $(m_V, \varepsilon) = (100 \text{ GeV}, 0.15)$.

The LHC is not a particularly good environment

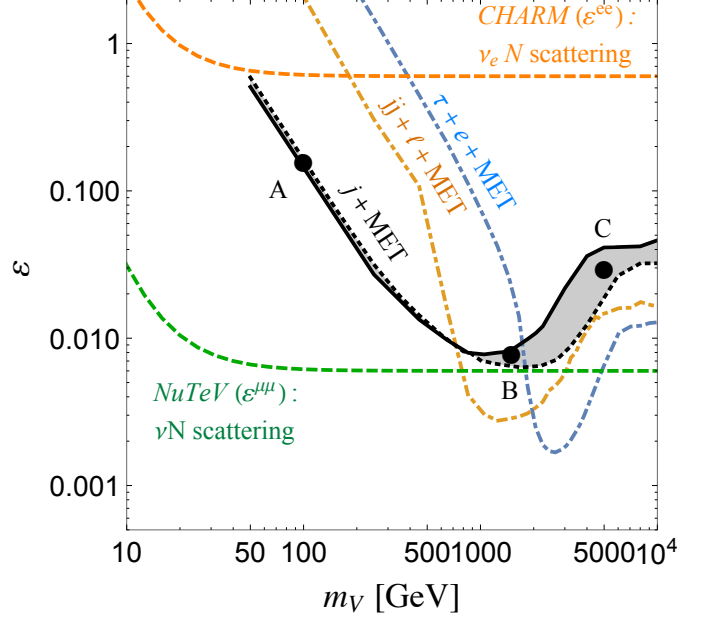


FIG. 6: In the mediator mass-coupling plane (m_V, ε) , we compare existing searches for NSI from neutrino-nucleus scattering to the LHC mono-jet limits derived in this paper. The upper curve in the gray band depicts the current monojet limits, while the lower curve shows the 13 TeV projection with 100 fb^{-1} . The dot-dashed curves represent the current multi-lepton constraints on NSI based on 8 TeV LHC data. Additional low-energy constraints on the NSI parameter $\varepsilon_{\alpha\beta}$ include NuTeV’s constraint on $\varepsilon_{\mu\mu}$ [95] and CHARM’s constraint on ε_{ee} [96]. For reference the constraint on $\varepsilon_{\tau\tau}$ is sufficiently weak that it does not appear on the plot (see [36]).

for discriminating neutrinos from DM in the light mediator limit. Although NuTeV’s constraint [95] on μ -flavored diagonal NSI shown as the orange dashed line in Fig. 6 allows us to conclude that this particular flavor structure is not responsible for anomalous missing energy events, the other flavor structures have much weaker constraints and cannot be excluded as potential explanations of LHC monojet signals. NSI with τ or e flavored interactions can simultaneously escape low-energy probes and multi-lepton searches at the LHC. Future data from dedicated low-energy experiments searching for $\nu_e - N$ or $\nu_\tau - N$ may help resolving this.

- **Benchmark B**, $(m_V, \varepsilon) = (1500 \text{ GeV}, 8 \times 10^{-3})$. Here, the LHC’s ability to discriminate NSI from the DM hypothesis is much more favorable given the strength of e, μ flavored NSI limits. Thus although monojet data will be at the discovery level, τ -flavored NSI is degenerate with a DM interpretation. However, since the $\tau + e + \text{MET}$ search utilized in the present paper, is not optimized for

NSI it is possible that a dedicated analysis could help resolve this.

- **Benchmark C**, $(m_V, \varepsilon) = (5 \text{ TeV}, 0.03)$.

This final benchmark is the most optimistic, as the discrimination between NSI and DM is robust. This is because there are two sensitive probes of NSI since both the $\tau + e + \text{MET}$ and $jj + \ell + \text{MET}$ channels yield stronger constraints than monojets. Thus for example, monojet data originating from this benchmark would already be excluded from being of NSI origin with present multi-lepton data.

Summarizing, the multi-lepton probes are crucial for distinguishing between DM and NSIs in benchmark C and partially in the case of benchmark B. For benchmark A input from additional low-energy experiments will be needed. These can be either DM or neutrino probes. For example, DM direct detection data can be used to determine the mass of the DM and bound the mediator mass [97–99].

Alternatively, in the case of neutrinos constraints on neutrino scattering will improve shortly. Using the methods outlined in [40], the COHERENT [100, 101] collaboration’s multi-target measurement of coherent elastic neutrino-nucleus scattering can be used to substantially strengthen the limits on NSI [100] from NuTeV [95] and CHARM [96].

Finally, thanks to the modification of neutrino oscillation probabilities that (vector) NSI induces, long-baseline and solar neutrino data will also further limit NSI. Future probes of NSI include long-baseline experiments such as NO ν A and DUNE [45], as well as atmospheric data from IceCube DeepCore [46], and solar neutrino data from DM direct detection experiments [102].

These complementary experimental searches will be tremendously useful in obtaining better sensitivity to NSI.

VI. CONCLUSION

If anomalous events with missing energy are found in the next run of the LHC, determining the nature of the “missing particles” will be of utmost importance. Given that neutrinos are the only confirmed source of missing energy to date, a neutrino interpretation would be quite natural. Moreover, such non-standard neutrino interactions are rather weakly constrained and could well produce sizeable $j + \text{MET}$ rates at the LHC. Here we investigated two useful tools that may aid in this discrimination: \cancel{E}_T shape analysis of monojet data, and multi-lepton data.

We found that NSI can be discriminated from DM based on \cancel{E}_T shape analysis if the DM mass is $\gtrsim 1 \text{ TeV}$.

Next, the $SU(2)$ charge of neutrinos implies that NSI contributes in channels involving charged leptons. This gives a simple discriminant between neutrino explanations of missing energy from singlet DM. To this end

we studied $jj + \ell + \text{MET}$ and $\tau + e + \text{MET}$ events to derive new limits on NSI. We have found that NSI mediators with masses $\gtrsim 800 \text{ GeV}$ can be fairly robustly discriminated from DM interpretations. This is because the above multi-lepton channels offer greater sensitivity at large mediator masses than monojets. In particular, for mediator masses greater than 1.5 TeV both channels are separately strong enough to discriminate between NSI and DM. Light mediator NSI remains hard to probe with LHC data, which underscores the importance of upcoming low-energy probes of NSI.

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Appendix: A UV Model of NSI

We would like to arrive at a simple completion of Eq. (3), which suggests a spin-1 completion given its Lorentz structure. Moreover, the main feature of Eq. (3) is that it implies stronger quark-neutrino interactions than quark-charged lepton interactions. A simple way to achieve is through the “baryonic portal” [103] (though see also [104–107]). In this class of models the quarks are charged directly under a new $U(1)'$ gauge symmetry. In addition there are new SM singlet fermions which also carry nonzero $U(1)'$ charge. We will refer to these as “baryonic neutrinos” for simplicity. When ordinary and baryonic neutrinos mass mix, the SM neutrinos effectively inherit a small piece of the new interaction. Thus one needs

$$\mathcal{L}_{NSI}^{UV} \supset g_V V_\mu (\bar{Q}\gamma_\mu Q + \bar{\nu}_1\gamma_\mu \nu_1) + y N H L + \lambda \phi N \nu_1 \quad (11)$$

where V is the gauge boson of the $U(1)'$ symmetry, N is a singlet fermion, ν_1 is the baryonic neutrino, and ϕ is a baryonic Higgs whose VEV provides a mass for the V . Crucially, once ϕ develops a VEV it allows mass mixing with N and hence N, ν_1 , and ν_α all mass mix. Note that in the above we have used the standard notation for the Lepton doublets, $L_\alpha = \begin{pmatrix} \nu_\alpha \\ \ell_\alpha \end{pmatrix}$, where $\alpha = e, \mu, \tau$,

Next, notice that when m_V, m_N are both large compared to the momentum flowing through the V propagator we can integrate out both new states to write

$$\varepsilon 2\sqrt{2}G_F = \frac{g_V^2}{m_V^2} \sin^2(2\theta_b), \quad (12)$$

where θ_b is the mixing angle.

An important theoretical constraint on the model comes from anomaly cancellation [108]. The least constrained possibility is when the new fermions are vector-like under the SM gauge group, but chiral under $U(1)_B$. Some of these fermion carry electric charge, meaning that they are very strongly constrained. The most conservative constraint comes from chargino searches at LEP and imply that these fermions be heavier than ~ 90 GeV [109].

Since the gauge boson mass is $m_V = g_V \langle \phi \rangle / 2$ and the vector-like fermions have a mass controlled by the new VEV, $m_f = \lambda \langle \phi \rangle$, the lower limit on the mass of the fermion translates into an upper limit on the size of the gauge coupling (also assuming $\lambda < \pi$)

$$g_V = \frac{2\lambda m_V}{m_f} \lesssim 6.3 \times 10^{-2} \left(\frac{100 \text{ GeV}}{m_f} \right) \left(\frac{m_V}{1 \text{ GeV}} \right) \quad (13)$$

Thus the anomaly considerations in Eq. (13) directly constrain the NSI coupling as:

$$\varepsilon \lesssim 310 \sin^2(2\theta_b) \quad (14)$$

Thus anomaly considerations on their own, are not a significant constraint on NSI models of this sort. However the LHC constraints found in this paper, $\varepsilon \lesssim 10^{-2} - 10^{-3}$, can be translated to a constraint on the mixing between the baryonic neutrino ν_1 and a SM neutrino, $\sin(2\theta_b) \lesssim (2 - 6) \times 10^{-3}$.

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